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## Evidence for a geomagnetic excursion recorded in the sediments of Lac St. Front, France: A link with the Laschamp excursion?

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**Abstract.** Anomalous paleomagnetic directions, accompanied by low intensities of natural remanent magnetization are recorded at 17 m depth in the sediments cored from Lac St. Front (Massif Central, France). The rock magnetic properties and the parameters characterizing anisotropy of susceptibility of samples taken from the sediment horizons carrying these anomalous directions, spanning some 30–40 cm, are identical to those of samples taken from the other stratigraphic intervals, carrying a record of normal geomagnetic secular variation. Therefore the sequence of anomalous directions is interpreted as a geomagnetic excursion. Furthermore, it is concluded that this excursion occurred at a time when the paleointensity field was low. The excursion is dated at about 33 <sup>14</sup>C (~37 ka B.P.) by correlating the susceptibility and paleomagnetic logs from Lac St. Front with the corresponding logs from the nearby Lac du Bouchet sedimentary sequence. The excursions in Lac St. Front can be averaged out with a triangular window of 20 cm. These smoothed excursions resemble the directional variations observed in the corresponding Lac du Bouchet interval. This finding indicates that the absence of this excursion in Lac du Bouchet may be due to a larger smoothing of the geomagnetic signal.

### Introduction

Since the discovery of the Laschamp excursion [Bonhommet and Babkine, 1967] several papers have reported geomagnetic excursions and polarity events within the normal polarity Brunhes Chron [Denham and Cox, 1971; Denham, 1976; Champion et al.; 1988 Nowaczyck et al.; 1994]. Excursions are generally defined as periods at which the virtual geomagnetic poles, calculated from the paleomagnetic directions at the locality, depart more than 45° from its time-averaged position for that epoch. Geomagnetic events are defined as short complete polarity intervals (10<sup>5</sup> years) [Merrill and McElhinney, 1983]. The absence of a correlation between different sedimentary sequences in the same time period and between sediments and volcanic rocks of the same age, however, has led to some doubts of the reliability of some excursions and events [Verosub and Banerjee, 1977; Thouveny and Creer, 1992]. Therefore considerable effort has been made to understand better the acquisition processes of the natural remanent magnetization (NRM) in order to explain the presence or absence of geomagnetic excursions in sedimentary records [Coe and Liddicoat, 1994; Dekkers et al., 1994].

In this paper we present the paleomagnetic results of the Maar lake sediments of Lac St. Front (France). The studied interval

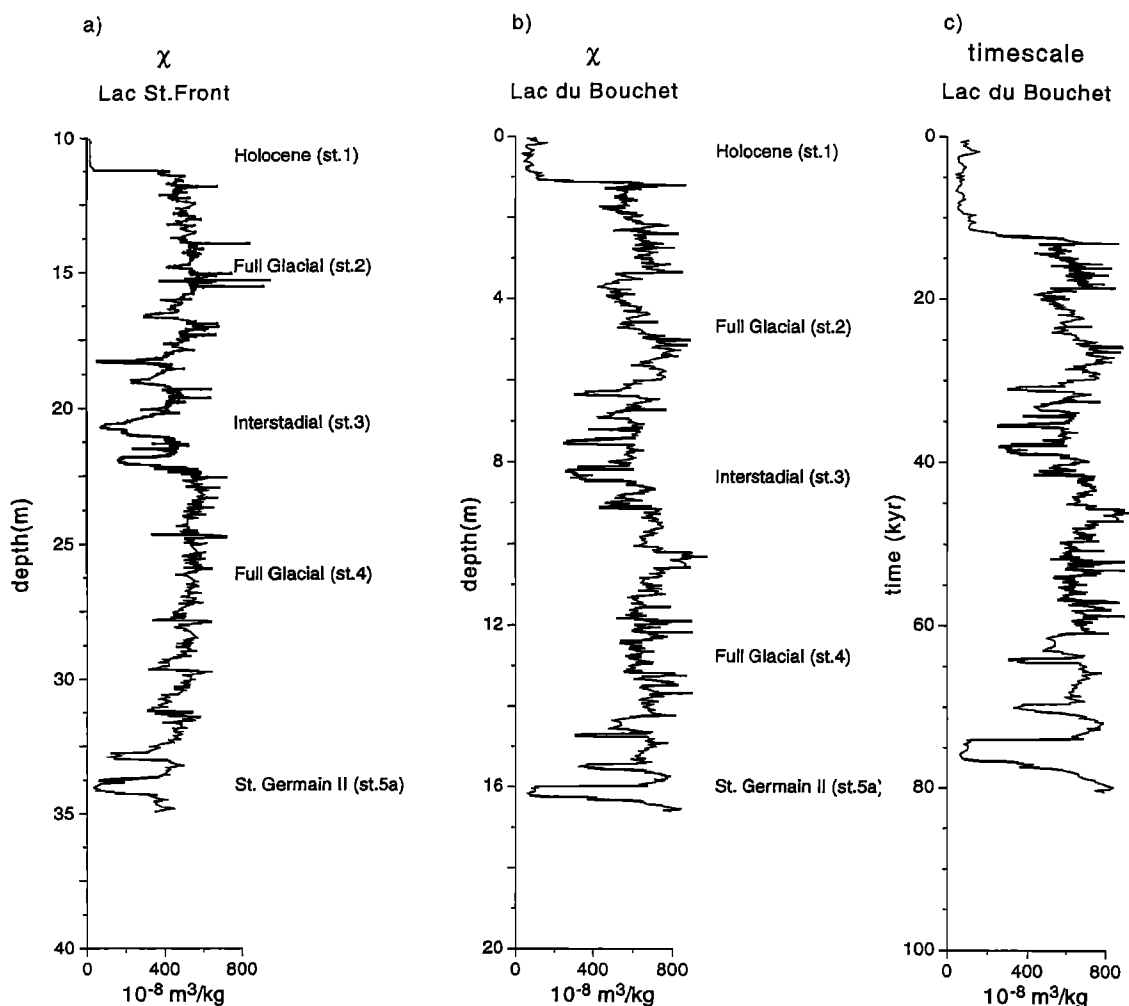
covers the period 12–45 kyr. The reliability of the directional and intensity changes of the NRM will be discussed after comparison with the results of the rock magnetic and anisotropy of susceptibility (AMS) study. Finally, the Lac St. Front paleomagnetic record will be compared with the paleomagnetic magnetic record of the nearby Lac du Bouchet [Thouveny et al., 1990].

### Site and Methods

Lac St. Front (longitude 3°E; latitude 45°N; altitude 1230 m) is a Maar lake located in the eastern Velay region of the Massif Central, France. The lake has a diameter of 600 m and a maximum depth of 6 m. In 1991, three parallel cores were collected from the central area of the lake. Cores A, B, and C have respective lengths of 45, 60, and 22 m.

In the laboratory the cores were split and subsampled every 2.5 cm with 8 cm<sup>3</sup> plastic boxes for paleomagnetic and rock magnetic studies. Intercore correlation was based on the susceptibility profiles of the individual cores. Since core B provided the longest sequence it was chosen as the "master" core. Depths of cores A and C were transformed into the depth scale of core B.

Down-core susceptibility logs (Figure 1a) show large susceptibility variations related to environmental changes [Thouveny et al., 1994]. High susceptibilities (>400×10<sup>-8</sup> m<sup>3</sup>/kg) are measured in grey to brown or silty clays deposited during cold climatic phases. Lower susceptibilities (<400×10<sup>-8</sup> m<sup>3</sup>/kg) are measured



**Figure 1.** (a) Magnetic susceptibility record of Lac St. Front sediments. The part containing small solid circles represents the studied interval. (b) Lac du Bouchet susceptibility record. In both figures the major climatic periods and their corresponding isotopic stage are marked. (c) The susceptibility record of Lac du Bouchet plotted on its time scale.

in organic or diatom rich gyttjas deposited during more temperate climatic conditions. Comparison of the Lac St. Front susceptibility record with the Lac du Bouchet susceptibility record (Figure 1), preliminary pollen study (V.Andrieu, personal communication, 1996) and organic carbon analysis [Rhoujjati, 1995] show that the upper 35 m of the Lac St. Front sedimentary sequence covers the last climatic cycle, from stage 5a to present time.

## Results

This paper is concerned with the paleomagnetic and rock magnetic observations in the interval 11.3–22.4 m depth. Correlation of the Lac St. Front susceptibility record with the susceptibility record of the nearby Lac du Bouchet shows that this interval covers the time period 12–45 <sup>14</sup>C kyr and has an approximate sedimentation rate of 40 cm/kyr (Figure 1). Most susceptibility minima between 17 and 22.5 m depth are accompanied with an increase in total organic matter [Rhoujjati, 1995] and can be related to temperate climatic events in the midglacial

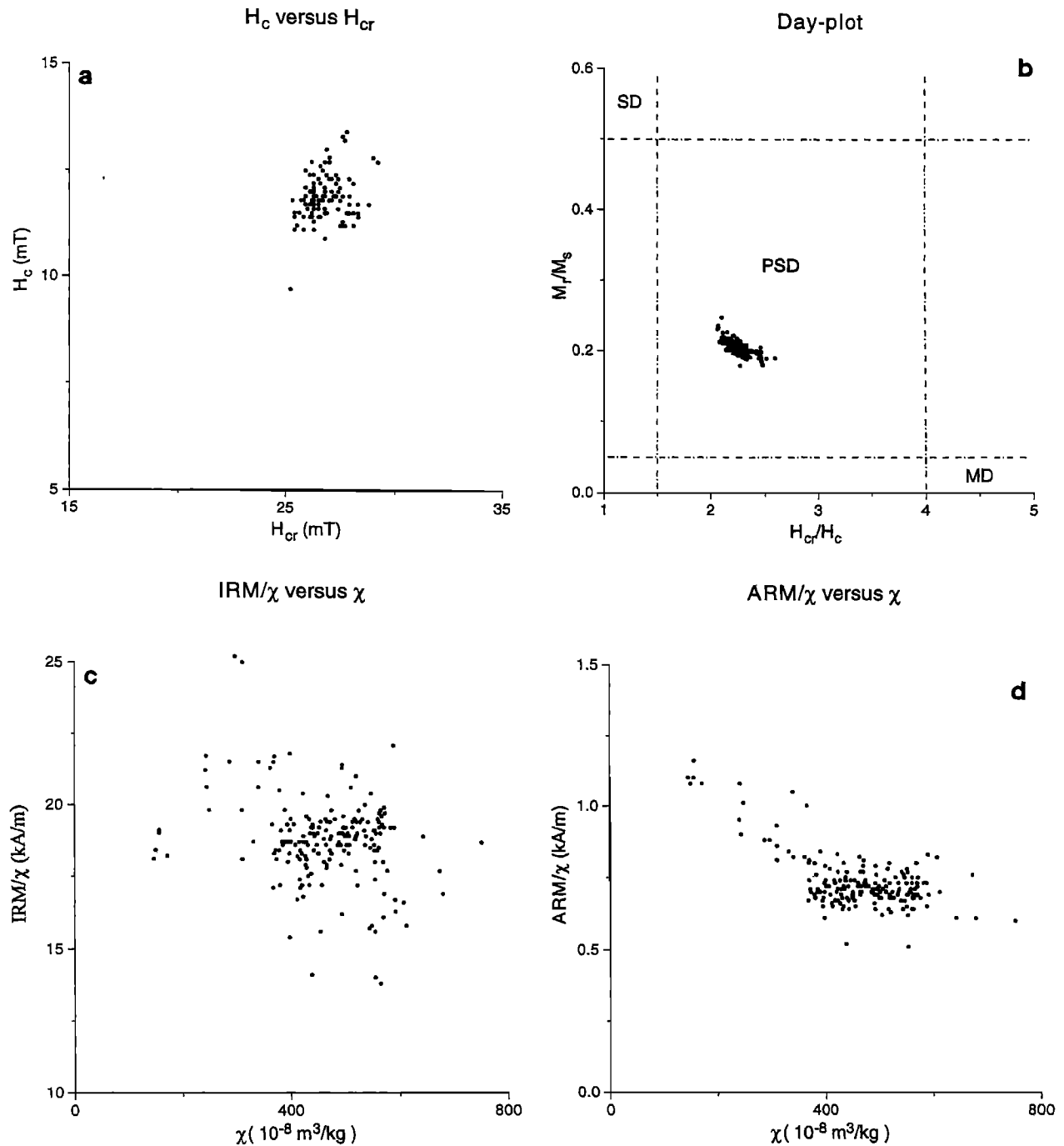
(equivalent to isotopic stage 3). The low susceptibilities at 18.3 m depth are recorded in a 5-cm-thick stony layer.

The abrupt change in susceptibility at 11.25 m corresponds with the Holocene/Pleistocene boundary. The interval 0–11.25 m is characterized by very low susceptibilities linked with a high total organic matter content and represents the Holocene.

In the studied interval the three parallel cores perfectly overlap. All these cores consist of 1 m sections. The diameter of the sections is 8 cm.

## Rock Magnetic Results

Rock magnetic measurements were performed on the sediments of core B to determine the composition and grain size of the magnetic minerals and to study which parameter is most suitable for normalization of the NRM. Low field susceptibilities ( $\chi$ ) were measured every 2.5 cm on a Bartington susceptibility bridge. Generally, susceptibilities are high (400–600  $\times 10^{-8}$  m<sup>3</sup>/kg) and show some small-scale variations. Slightly higher susceptibilities are measured at 15.5 m depth in a more silty lithology.



**Figure 2.** Rock magnetic parameters for the studied interval. (a)  $H_c$  versus  $H_{cr}$ , (b)  $M_r/M_s$  versus  $H_{cr}/H_c$ , (c) IRM/ $\chi$  versus  $\chi$  and (d) ARM/ $\chi$  versus  $\chi$ .

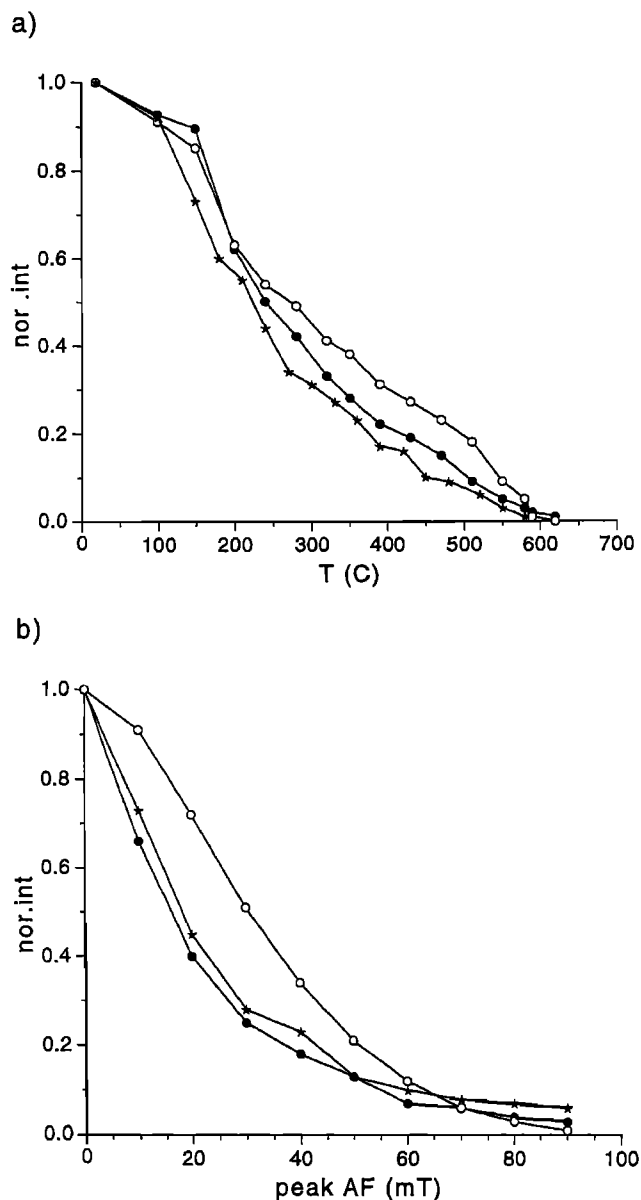
Lower susceptibilities were measured at depths 16.6, 18.3, and 19.0 m (Figures 1a and 8a).

Magnetic concentrates were obtained by passing the dissolved sediments through a 1 T field between two poles of an electromagnet. Scanning electron microscope images on these concentrates identify detritus as being the main magnetic minerals. Microprobe analysis reveals a Ti/Fe ratio generally less than <0.3.

Thermomagnetic runs were carried out with an ultrasensitive modified horizontal translation Curie balance [Mullender *et al.*, 1993] on bulk sediments. These  $M_s$ - $T$  runs show a maximum

unblocking temperature of about 580°C and confirm that magnetites with some Ti content are the main magnetic carriers.

Hysteresis experiments were performed on an alternating gradient magnetometer (MicroMag). Changes in the remanence ratio  $M_r/M_s$ , the coercive force  $H_c$ , the remanent coercive force  $H_{cr}$ , the coercivity ratio  $H_{cr}/H_c$  and the additional hysteresis parameter  $M_r/\chi_{Hrs}$ , defined as the ratio of saturation magnetization by the slope of the hysteresis loop at zero field [Vlag *et al.*, 1996], are limited throughout the studied interval.  $H_c$  and  $H_{cr}$  are  $\sim 12.5$  and  $\sim 26$  mT, respectively (Figure 2a). The hysteresis ratios  $M_r/M_s$  and  $H_{cr}/H_c$  suggest that the magnetic



**Figure 3.** (a) Thermal and (b) alternating field decay curves for IRM (solid circles), ARM (open circles) and NRM (stars).

carriers are pseudo-single domain grains [Day *et al.*, 1977] (Figure 2b). Hysteresis experiments also show that the para- and diamagnetic susceptibility at high fields ( $\chi_{HF}$ ) contributes ~3% to the low-field susceptibilities ( $\chi$ ).

Isothermal remanent magnetization (IRM) was implanted with a 1 T field. Typical IRM intensities are 70-110 mAm<sup>2</sup>/kg. IRM/ $\chi$  ratios show only small variations in this part of the Lac St. Front sequence (Figure 2c). As  $\chi$  is not corrected for  $\chi_{HF}$ , small variations in the IRM/ $\chi$  ratios might be caused by the small para- and diamagnetic contribution to  $\chi$ .

Anhyseretic remanent magnetization (ARM) was implanted with a Schonstedt demagnetizer using a 90 mT alternating field (AF) superimposed on a 0.1 mT steady field. Typical ARM intensities range from 2.5 to 4 mAm<sup>2</sup>/kg. ARM/ $\chi$  ratios increase with a decreasing susceptibility for specimens having a susceptibility lower than  $350 \times 10^{-8}$  m<sup>3</sup>/kg (Figure 2d). This suggests a relative increase in ARM with decreasing concentration.

Thermal demagnetization of the IRM and ARM reveals that ARM is carried by thermally more stable grains than the IRM. The unblocking temperatures of IRM and ARM fall between 580°C and 610°C (Figure 3a), slightly too high for pure magnetite. This high temperature might be related to some oxidation of the magnetite. AF demagnetization of the IRM and ARM along three orthogonal axes shows that the median destructive fields of IRM ( $MDF_{IRM}$ ) and ARM ( $MDF_{ARM}$ ) are ~17 mT and ~25 mT, respectively (Figure 3b). Like the hysteresis parameters, AF and thermal blocking spectra of IRM and ARM do not show important changes in the studied section. The small variations in all concentration-independent rock magnetic parameters favor the reliability of the NRM signal.

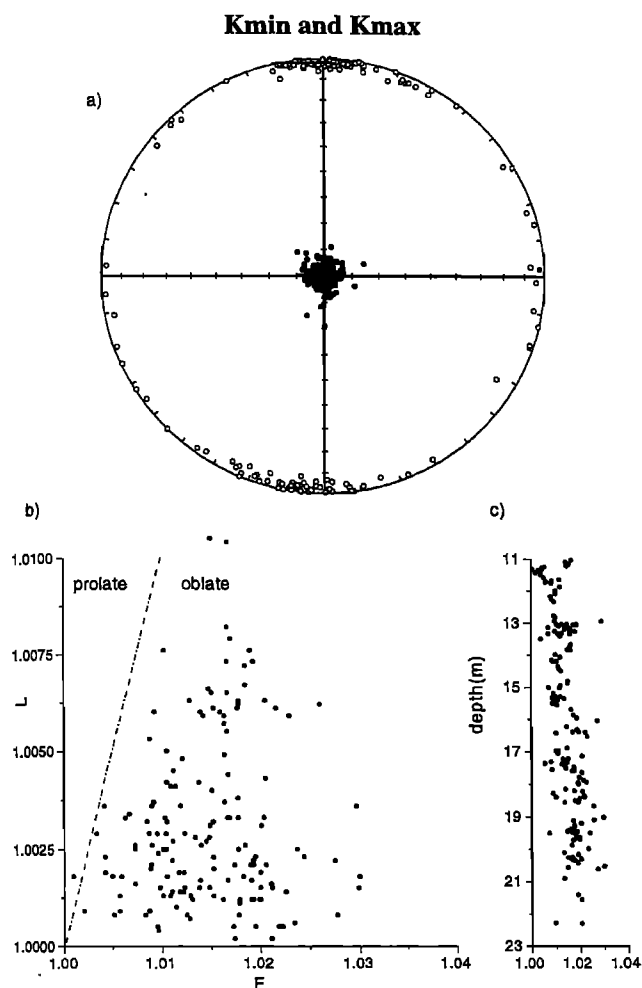
### Anisotropy of Susceptibility

Anisotropy of the magnetic susceptibility (AMS) can be used to study tilt and physical disturbance of the sedimentary layers [Rochette *et al.*, 1992; Collombat *et al.*, 1993; Quidelleur *et al.*, 1995a). Although AMS might be influenced by paramagnetic and diamagnetic minerals and is more sensitive to coarser ferromagnetic fractions than the remanence, this technique can be used to check the reliability of the NRM directions, because, if the AMS suggests tilt and/or deformation of the sedimentary layers, it is likely that the orientation of the remanence carriers is also affected by this tilt/deformation.

AMS measurements were routinely performed every 7.5 cm along core B. From layers showing anomalous directions, additional samples were collected for AMS measurements. AMS measurements were performed on a KLY-2 Kappa-bridge and the AMS tensor was calculated according to Jelínek [1977]. This tensor can be visualized as an ellipsoid having three principal axes: Maximum, intermediate and minimum susceptibility ( $K_{max}$ ,  $K_{int}$  and  $K_{min}$ ). The magnetic lineation (L) is defined by  $K_{max}/K_{int}$ , the magnetic foliation (F) by  $K_{int}/K_{min}$ . For these sediments L is smaller than F, indicating that the AMS ellipsoid is oblate (Figure 4b). As the directions of  $K_{max}$  are confined into one axis and the cores were collected without azimuthal orientation (Figure 4a), it can be concluded that the small lineation (1.002-1.007) is introduced during the subsampling of the cores. Inclinations of  $K_{min}$  are generally higher than 80° (Figure 3a). Variations in lineations and  $K_{min}$  are limited (Figures 4a and 4b). The regular increase of F downcore is due to compaction. Very low F values are observed at 11.5 m (Figure 4c). The near absence of foliation just below the Holo-ene/Pleistocene boundary suggests a reworking (bioturbation?) of the sediments at this level. AMS measurements do not indicate tilt or disturbance of the sedimentary layers in the studied section.

### Natural Remanent Magnetization

NRMs were measured on discrete specimens with a 2 G cryogenic magnetometer (model 760 R). Typical NRM intensities range between 300 and 650 mA/m. For a complete analysis of the NRM, 33 samples were selected for stepwise alternating field (AF), and 25 samples were selected for stepwise thermal demagnetization of the NRM.



**Figure 4.** Results of the AMS measurements. (a) Directions of  $K_{\text{MIN}}$  and  $K_{\text{MAX}}$  plotted on a stereogram. Closed (open) circles denote directions of  $K_{\text{MIN}}$  ( $K_{\text{MAX}}$ ). Note that  $K_{\text{MAX}}$  directions are confined to one axis. (b) Lineation (L) versus foliations (F). (c) Foliation versus depth. Note that F is almost zero at 11.25 m depth and increases slightly with increasing depth.

Stepwise AF demagnetization of the NRM demonstrates the presence of one principal magnetization component, after removal of a weak viscous component. Median destructive fields of the NRM range between 10 and 20 mT (Figures 5a, 5b and 5c). Progressive thermal demagnetization of the NRM shows the presence of a principal magnetization component, which is removed between 300 and 580°C (Figures 5d, 5e and 5f). Some demagnetization diagrams indicate the presence of a slightly different magnetization component removed at temperatures below 300°C (Figures 5d and 5e).

Lower NRM intensities and anomalous NRM directions are measured between 16.6 and 18.2 m depth. These anomalous directions are also carried by one principal magnetization component (Figures 5g, 5h and 5i). Demagnetization diagrams of these specimens, however, show a more complex behavior due to a larger viscous component and more spurious magnetization components.

Directions of the principal magnetization component were determined by fitting a least squares line [Kirschvink, 1980]

through usually more than five demagnetization steps. For the AF demagnetization diagrams, the range of the included demagnetization steps falls between 10 and 80 mT AF. For the thermal demagnetization diagrams, the principal magnetization component was usually determined from the demagnetization steps ranging from 300° up to 550°C. For specimens with anomalous directions, principal magnetization components are determined from the same range of (AF and thermal) demagnetization steps. However, as the relevant demagnetization diagrams are more affected by spurious magnetization components, the best fitting line is generally drawn through a smaller number of demagnetization steps.

Directions derived from AF and thermal demagnetization diagrams are similar. In the next section, a more detailed description of the NRM directions will be given.

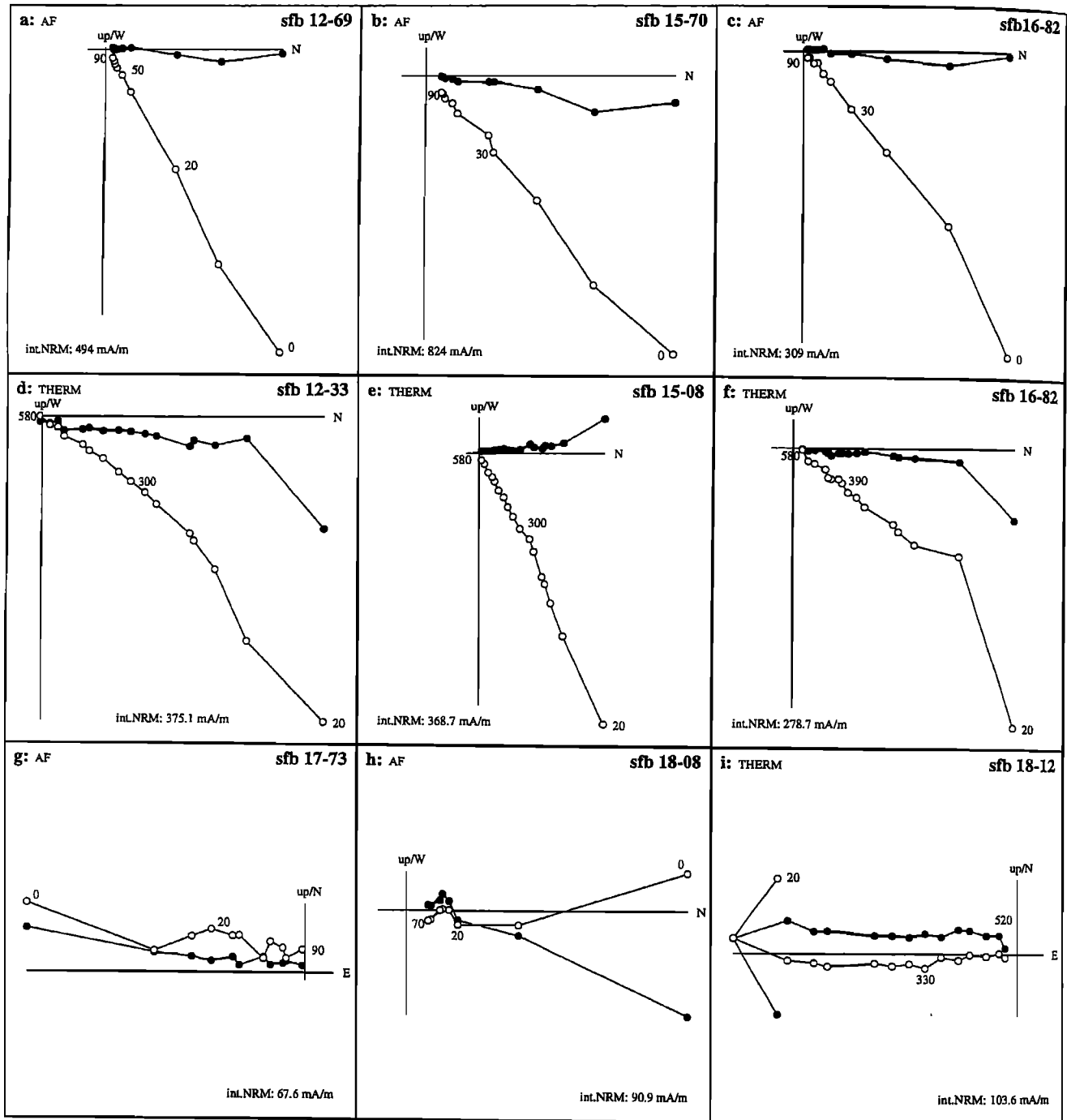
Monitoring the decay in NRM intensity in a zero field was done by placing a sample in the 2G cryogenic magnetometer and measuring the magnetization every 6 s. After 30 min all samples showing anomalous directions (16.6–18.2 m depth) have their NRM intensity decreased by ~15%, while the NRM intensity of other samples remains constant (Figure 6).

#### Construction of the Directional Records

NRM directions were measured every 2.5 cm by using cubic samples of 8 cm<sup>3</sup>. On the basis of the demagnetization diagrams of the pilot samples, AF demagnetization of the NRM was performed by using peak alternating fields of 15 and 30 mT. For core B, NRMs were also demagnetized at 60 mT.

As the core sections were collected without azimuthal orientation, declinations of the individual section had to be corrected. Generally, this correction was made by shifting the measured declinations per individual section to a mean of 360°. This procedure was checked by comparing the corrected declination profiles with the declination variations of the parallel cores. (Section limits of parallel cores are usually situated at different stratigraphic depths.) If this check failed or in the cases that (1) large declination variations prevented the calculation of a significant mean declination value per section (interval 16.6–18.2 m) or (2) shifted declinations in the lowermost 8 cm of one section differ more than 10° from the shifted declinations in the uppermost 8 cm of the underlying core section, the declination profiles were shifted such that the mean of the shifted declinations in the lowermost 8 cm of the section concerned equals the mean of the shifted declination in the uppermost 8 cm of the underlying core section.

No systematic differences in shifted declinations and inclinations between the different cores are observed. In Figure 7, this finding is shown for the NRM directional variations after 15 mT AF demagnetization (NRM<sub>15</sub>). Therefore the declination and inclination records of the three individual cores were merged, and merged declination and inclination records are presented (Figure 8). Unless it is otherwise stated, we refer to these merged records as declination and inclination records. Declination and inclination profiles of NRM<sub>15</sub> agree with the directions of the principal magnetization components derived from the AF and thermal demagnetization diagrams (Figures 8b, 8c). NRM<sub>15</sub> in-

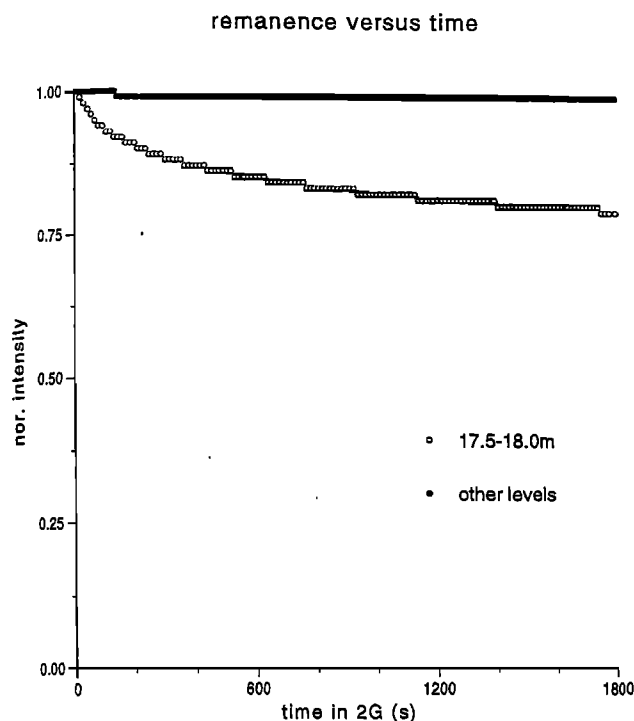


**Figure 5.** Typical demagnetization diagrams for stepwise (a, b, c) AF and (d, e, f) thermal demagnetization. (g, h) AF and (i) thermal demagnetization diagrams of specimens having anomalous directions. Note that NRM intensities of these specimens are weaker.

clination and declination records also agree with directional records obtained after 30 and 60 mT AF demagnetization. Therefore, the  $\text{NRM}_{15}$  directional records were considered as representative of the characteristic directions of the NRM.

Except for the 16.6 to 18.2 m depth interval, inclination and declination records of  $\text{NRM}_{15}$  oscillate around the direction of the field generated by a geocentric axial dipole at this site (declination  $360^\circ$ ; inclination  $62^\circ$ ). Slightly shallower inclinations are measured at 11.8 and 13 m depth. At 15.8 m depth

steeper inclinations and an easterly declination swing are observed (Figures 8 b and 8c). The most remarkable feature of this record, however, consists of the anomalous directions recorded between 16.6 and 18.2 m. In this interval, steep inclinations ( $>70^\circ$ ) are followed by shallow and negative inclinations. Declinations in this interval are characterized by a large dispersion followed by a westerly declination swing. Although the amplitude and scatter of these directional variations vary between the individual cores, all cores show the same similar trends between



**Figure 6.** NRM intensity measured during 30 min. in the field free space of the 2G cryogenic. Open circles denote a typical example for specimens with anomalous directions. Solid circles denote a typical example for specimens of the other parts of the studied section.

16.6 and 18.2 m depth (Figure 7). Core B shows the largest scatter and directional variations. The NRM<sub>15</sub> directional variation records of the individual cores show that in the steep inclination interval a westerly and easterly declination swing are observed. Because of the different amplitudes of these swings in the individual cores, the merged declination record is scattered in this interval (Figure 8b). Calculating virtual geomagnetic poles (VGPs) from the inclination and declination variations between 16.6 and 18.2 m depth shows that these directional variations satisfy the criteria for an excursion [Merrill and McElhinney, 1983].

### Normalization of NRM Intensities

For core B, NRM<sub>15</sub> intensities were normalized by IRM. We chose to normalize NRM<sub>15</sub> intensities instead of NRM intensities, because NRM<sub>15</sub> intensities are less influenced by viscous remanent magnetization (VRM). Generally, NRM<sub>15</sub> intensities are 50-60% of initial NRM intensities. For specimens with anomalous directions (16.6-18.2 m depth), NRM<sub>15</sub> intensities are 40-60% of initial NRM intensities.

IRM was preferred as normalizer of NRM<sub>15</sub> over  $\chi$ , because, in contrast to  $\chi$ , IRM intensities are not influenced by superparamagnetic grains and paramagnetic and diamagnetic minerals. IRM was preferred over ARM, because coercivity spectra as well as unblocking temperature spectra of IRM are more similar to NRM than are those of ARM (Figure 3). Another argument in favor of IRM is that ARM intensities are slightly enhanced in "low" susceptibility intervals, while this enhancement does not

exist for IRM intensities. (Figures 3c and 3d). IRM blocking spectra are constant for the studied sections (Figure 9). Therefore, normalizing NRM<sub>15</sub> with IRM intensities measured after 15 mT AF demagnetization (IRM<sub>15</sub>) provides similar results to those achieved by normalizing NRM<sub>15</sub> with "untreated" IRM.

To attribute variations in the NRM<sub>15</sub>/IRM ratio to relative changes of the paleointensity field, one has to eliminate rock magnetic effects on this ratio. Therefore we classified the NRM<sub>15</sub>/IRM ratios into two groups (I and II). The idea behind this classification is to relate only those NRM<sub>15</sub>/IRM variations to intensity changes of the geomagnetic field, which are recorded in sedimentary layers having the same magnetic concentration and properties. We emphasize that the selection criteria for this classification are arbitrary and specific for these sediments.

NRM<sub>15</sub>/IRM ratios are classified into group I, if their associated rock magnetic parameters satisfy the following criteria: (1)  $400 \times 10^{-8} \text{ m}^3/\text{kg} < \chi < 600 \times 10^{-8} \text{ m}^3/\text{kg}$ , (2)  $15 \text{ kA/m} < \text{IRM}/\chi < 20 \text{ kA/m}$ , (3)  $0.4 \text{ kA/m} < \text{ARM}/\chi < 1.1 \text{ kA/m}$ , and (4)  $0.185 < M_r/M_s < 0.215$ . NRM<sub>15</sub>/IRM ratios are classified into group II, if their rock magnetic parameters do not satisfy one (or more) of the criteria mentioned above. Magnetic concentration and rock magnetic variations are limited in group I. Therefore variations in NRM<sub>15</sub>/IRM ratios belonging to this group can be related to intensity changes of the geomagnetic field. Although variations in the NRM<sub>15</sub>/IRM ratios of group II could also be caused by paleointensity changes, it is also possible that they are related to changes in magnetic concentration, grain size, or composition. Therefore we do not attribute them to intensity changes of the paleofield.

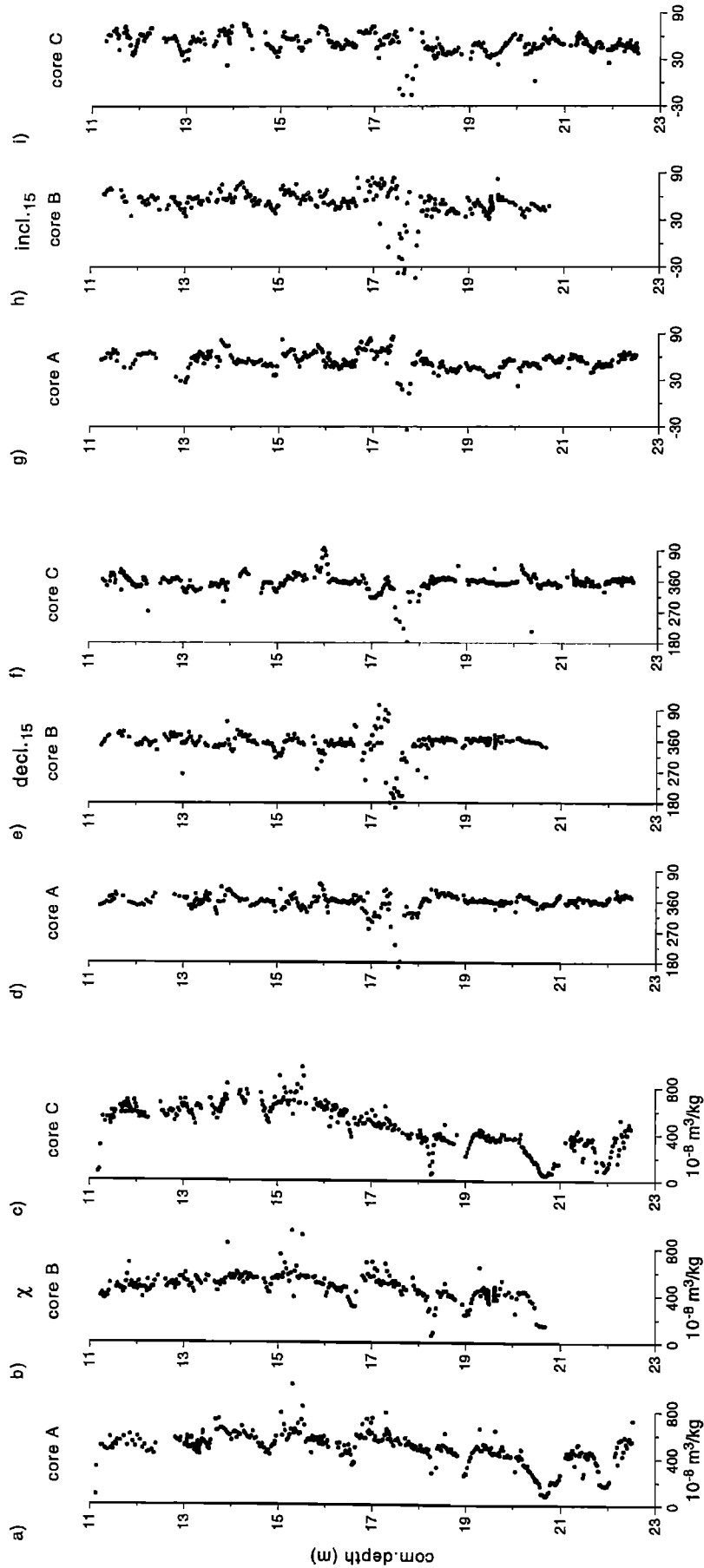
With the use of this method, 127 ratios were classified into group I. The remaining 66 ratios of group II are generally located in the depth intervals having low or very high  $\chi$  values (around 15.5, 16.6, 18.3, and 20.8 m depth) (Figures 8a and 8d).

Taking only into account group I, we observed high NRM<sub>15</sub>/IRM ratios ( $\sim 1.5 \times 10^{-3}$ ) values are observed between 11.3 and 15 m and between 19 and 22 m depth. Lower NRM<sub>15</sub>/IRM ( $\sim 0.8 \times 10^{-3}$ ) ratios are observed in the depth intervals 15-16.5 m and 18.2-19 m. The most striking feature, however, is the marked minimum between 17.2 and 17.6 m. These NRM<sub>15</sub>/IRM ratios are  $0.2 \times 10^{-3}$ , about 13% of the high NRM<sub>15</sub>/IRM ratios (Figure 7d). This minimum in NRM<sub>15</sub>/IRM corresponds to the anomalous NRM<sub>15</sub> directions. The strictness of the reliability criteria chosen for group I convinces us that these low NRM<sub>15</sub>/IRM ratios reflect low intensities of the paleofield.

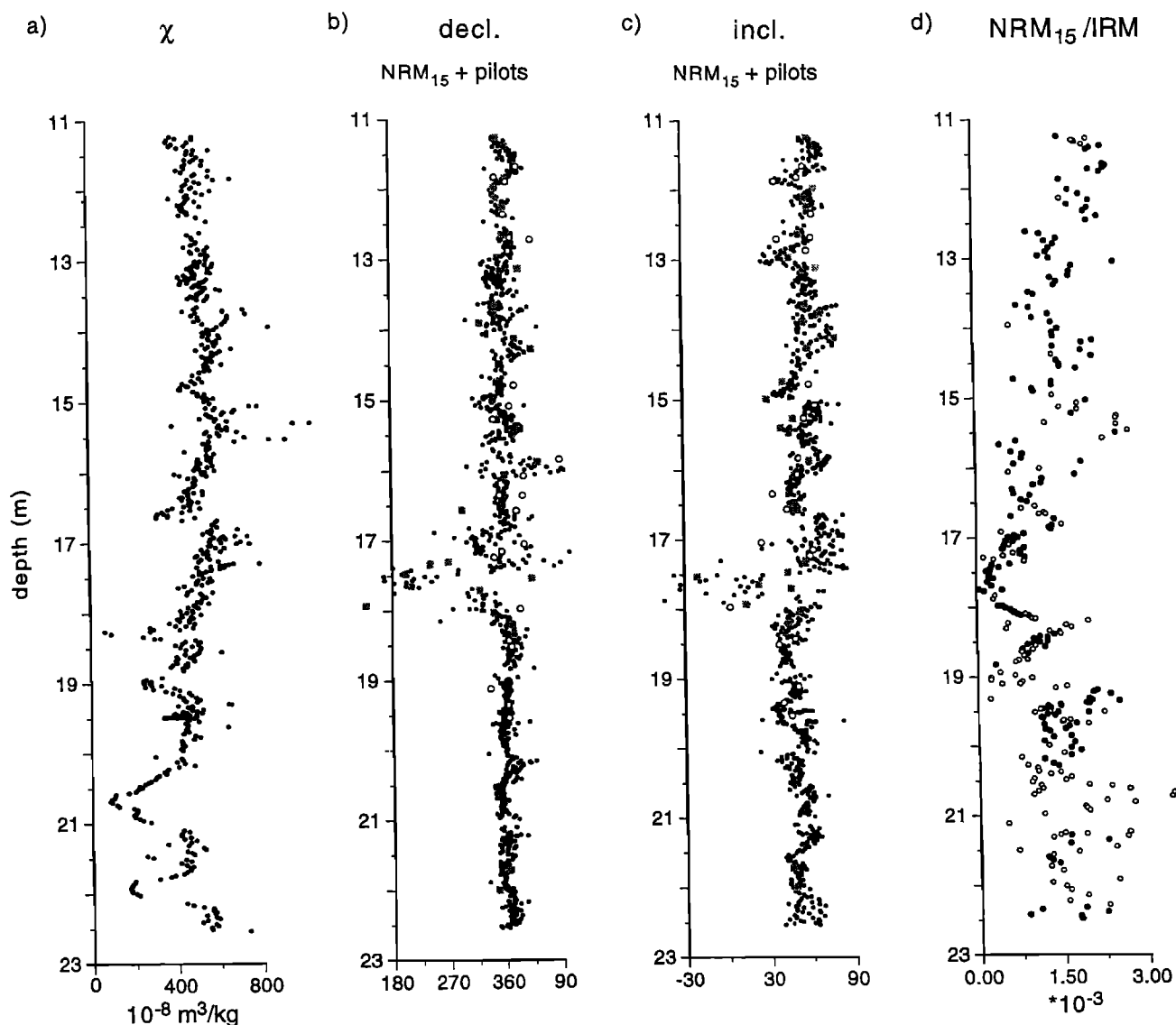
### Reliability of the Excursion Directions

As mentioned before, the most remarkable features in these paleomagnetic records are the anomalous directions and the minimum in absolute and normalized NRM<sub>15</sub> intensities between 16.6 and 18.2 m depth. An interval with a higher organic matter content and lower susceptibilities marks the upper limit of the anomalous direction interval, while the lower limit of this interval is characterized by a 5-cm-thick stony layer (Figures 10a and 10b). Although the upper and lower limits of the excursion directional interval seem to be related to lithological and rock magnetic changes, the rock magnetic parameters and the AMS parameters (Figures 10c, 10d, 10e, 10f, 10g, 10h) in this 1.6 m interval itself do not differ from other stratigraphic intervals, while the NRM directions are anomalous (Figure 8h, i) and absolute and normalized NRM<sub>15</sub> intensities are very low (Figure





**Figure 7.** (a)(b)(c) Susceptibility and paleomagnetic records for core A, B, C. The plotted (d)(e)(f) declination and (g)(h)(i) inclination records measured after 15 mT AF demagnetization. Declinations are shifted (see text). All records are plotted on the common depth scale, which was based on the intercore correlation of the susceptibility records of the individual cores. Declinations are shifted (see text).



**Figure 8.** (a) Stacked susceptibility and (b,c) paleomagnetic records of the studied interval, with declination and inclination records after 15 mT AF demagnetization, and directions of primary and characteristic magnetization components derived from the thermal (open circles) and AF (squares) demagnetization diagrams. (d)  $NRM_{15}/IRM$  record. In the latter figure solid (open) circles denote  $NRM_{15}/IRM$  ratios classified into group I (II) (see text).

10i, j, k, l, m). Hence, AMS and rock magnetic parameters do not indicate a rock magnetic or a depositional origin for this different NRM behaviour while the low  $NRM_{15}/IRM$  (and  $NRM_{15}/IRM_{15}$ ) ratios are classified into the "reliable" group I. This distinction helps to reject a rock magnetic or a sedimentary fabric as origin for these anomalous NRM directions.

In this interval, NRM characteristics are slightly different: (1) NRM intensities decrease ~15% after 30 min in the field free space of the 2 G cryogenic, (2) demagnetization diagrams are more affected by spurious magnetization components and (3) NRM directional profiles are more scattered. It is unlikely that this scatter can be attributed to the lower NRM intensities, because magnetic moments ( $NRM > 5.0 \times 10^{-7} \text{Am}^2$ ,  $NRM_{15} > 2.5 \times 10^{-7} \text{Am}^2$ ) are still well above the noise level of the 2 G cryogenic ( $\sim 1 \times 10^{-9} \text{Am}^2$ ) in our laboratory. Hence, it is more likely that the more scattered directions in this interval can be

attributed to the viscous and spurious magnetization components.

*Quidelleur et al.* [1995b] demonstrated in their redeposition experiments that changing the ambient magnetic field intensity may lead to a different NRM acquisition (and thus behavior). Below a critical field intensity (~10% of the present-day field) the magnetic alignment is extremely poor. It is well possible that the increase in spurious magnetization components and the increased scatter in the directional records between 16.6 and 18.2 m depth are related to poor alignment of the magnetic grains due to low geomagnetic field intensity.

It is suggested that the orientation of the magnetic grains deposited in a low field intensity are controlled by hydrodynamical forces [*Quidelleur and Valet*, 1994]. Because of these forces, inclinations become shallow, and NRM directions do not accurately record the geomagnetic field anymore. If this effect is domi-

nating, inclinations accompanied by (extremely) weak normalized NRM intensities should be shallow. In our site, low  $\text{NRM}_{15}/\text{IRM}$  intensities are measured, while inclinations show a succession of steep and low values. The absence of a correlation between low inclinations and low  $\text{NRM}_{15}/\text{IRM}$  intensities and the large declination swings observed in this interval leads us to the conclusion that large variations of the geomagnetic field intensity have probably occurred during this period.

To summarize, after a critical comparison between the excursions directions and the results of the rock magnetic and AMS study and after explaining the slightly different NRM behavior in this interval, we conclude that large directional variations of the NRM between 16.6 and 18.2 m depth reflect a geomagnetic excursion linked with a low field intensity.

### Correlation of the Lac St. Front Records With the Lac du Bouchet Records and Age of the Excursion

Unfortunately, no independent dating of the Lac St. Front sediments exists. All  $^{14}\text{C}$  age determinations in the studied interval had to be rejected because of excessively low carbon content. Therefore the age of the excursion was estimated by (1) correlating the Lac St. Front sedimentary sequence with that of Lac du Bouchet and (2) using the Lac du Bouchet depth-time transformation [Thouveny *et al.*, 1990].

Lac du Bouchet lies only 40 km from Lac St. Front, is situated at the same altitude, and has a very similar local morphology and size of the catchment area. Hence both sedimentary records should have recorded the same climatic events and geomagnetic field. Thouveny *et al.* [1994] showed that the susceptibility changes at Lac du Bouchet and Lac St. Front are largely influenced by a climatic signal. Hence, after elimination of local effects on the susceptibility records of the individual sites, we are justified in correlating the susceptibility records of both sequences. As mentioned before, from a geomagnetic point of view we are justified in correlating the paleomagnetic records of Lac St. Front and Lac du Bouchet. However, in practice, small discrepancies between these records may be observed. These possible discrepancies may be related to differences in NRM acquisition processes, caused by different sedimentation rates and different rock magnetic properties. This finding implies that it is not straightforward to base the correlation of the Lac St. Front and the Lac du Bouchet sequence on the paleomagnetic records. Nevertheless, the paleomagnetic records can be used to examine the validity of the susceptibility correlations. Therefore the correlation between the Lac St. Front and the Lac du Bouchet sequence is based on (1) correlation of the susceptibility records and (2) checking this correlation by comparing the paleomagnetic records of these sites.

As in Lac du Bouchet, the full Glacial/Holocene boundary is well identified in Lac St. Front; this identification provides a good a first-order element for correlating the two sequences (Figure 11). Correlation of the two sites in the full and midglacial is based on eight correlation points, labelled sf1-sf8

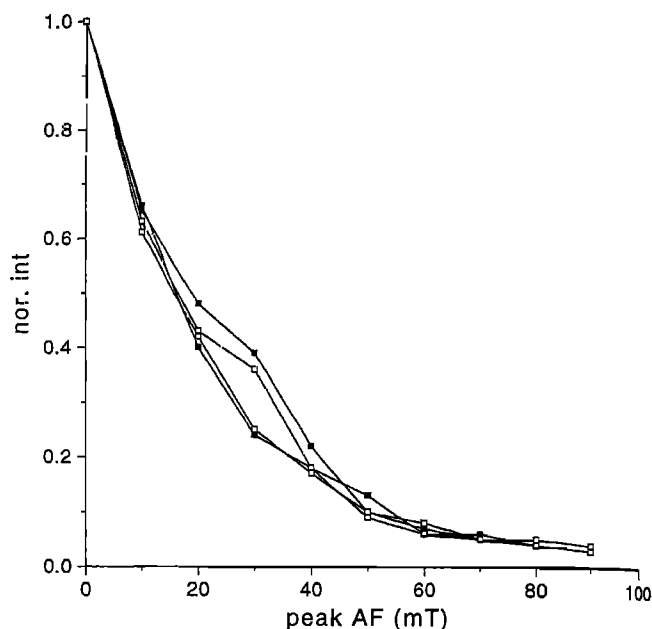


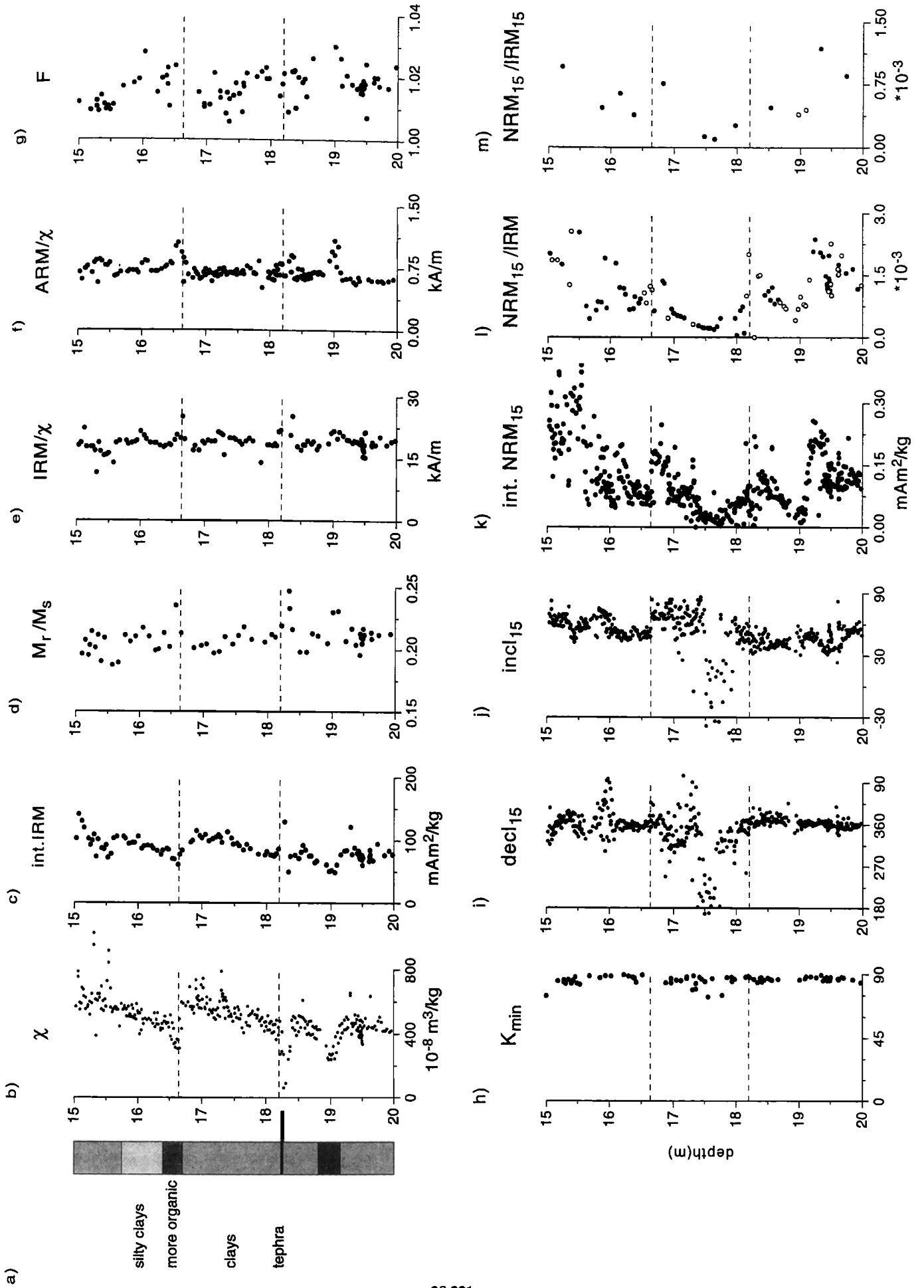
Figure 9. Typical IRM AF decay curves for the specimens with anomalous directions and low normalized intensities from the 17.5-18.0 m depth interval (open squares) and for specimens from other depths (solid squares).

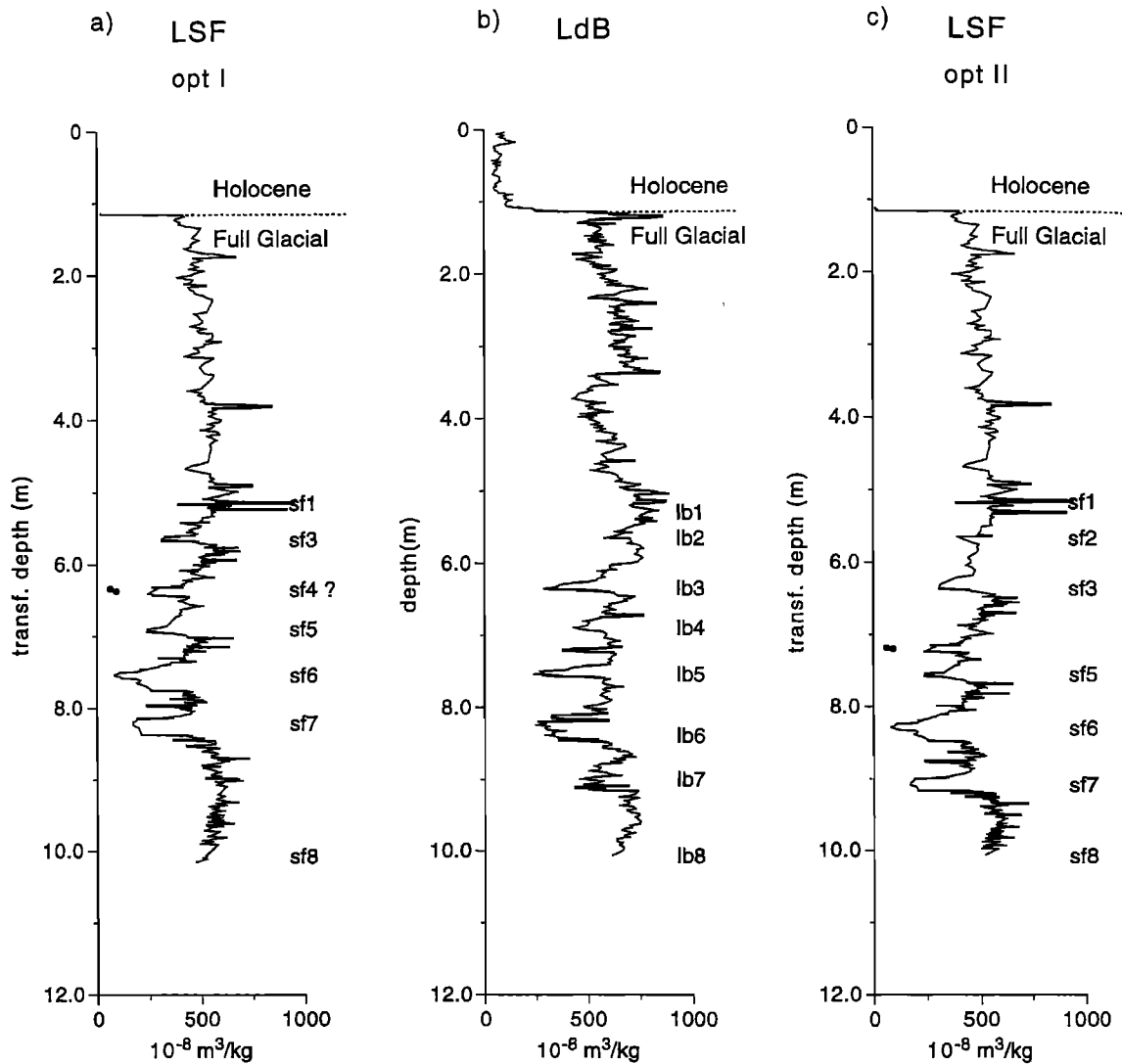
in the Lac St. Front susceptibility record and lb1-lb8 in the Lac du Bouchet susceptibility record. It should be noted that the use of correlation point sf4? is not straightforward. These low susceptibilities are located around a thin stoney layer in Lac St. Front, which was not identified in Lac du Bouchet. Although the low susceptibilities measured in this layer itself are excluded for the correlation, it might be that the low susceptibilities just above the stoney layer are related to this local signal. In this case, it is, of course, not correct to use sf4? as a correlation point.

Susceptibility maxima sf1 and lb1 correlate well. Below this depth two correlation options exist (I and II). Option I is based on the correlation of the Lac St. Front susceptibility minima sf3, sf4?, sf5, sf6, sf7 and sf8 with the Lac du Bouchet susceptibility minima lb2, lb3, lb4, lb5, lb6, lb8 (Figure 9a, b). Correlation option II is obtained after correlating sf2, sf3, sf5, sf6, sf7 and sf8 with lb2, lb3, lb5, lb6, lb7 and lb8 (Figure 11b and 11c).

Plotting the Lac St. Front susceptibility records on the Lac du Bouchet depth scale according to these two correlations shows that both options are acceptable (Figure 11). Comparison of the original Lac St. Front depths with the transformed depths (Figure 12a) reveals that for both options the transformed original depth ratio does not show large variations between the separate correlation points, confirming that both correlations are acceptable. Correlation option I implies that the excursions directions are situated between transformed depths 5.68 and 6.35 m. According to the Lac du Bouchet depth-time transformation, this depth corresponds to an age of ~30 ka. Option II implies that the excursions directions are situated between 6.35 and 7.09 m transformed depth, which corresponds to an age of ~33

Figure 10. (opposite) (a) Lithological column and detailed records of the (b)-(f) rock magnetic, (g, h) AMS and (i)-(m) paleomagnetic data. The paleomagnetic data are stacked from the individual cores. In the normalized  $\text{NRM}_{15}$  intensity records (open) solid symbols denote  $\text{NRM}_{15}/\text{IRM}$ ,  $\text{NRM}_{15}/\text{IRM}_{15}$  ratios belonging to group I(II) (see text).





**Figure 11.** (a,c) The two correlation options between the Lac St Front and (b) the Lac du Bouchet susceptibility records. For the Lac St. Front susceptibility record the line is drawn through the susceptibilities measured on the discrete specimens of core B. Solid circles denote the low susceptibilities measured in the stony layer (see text). Labels denote the correlation points between the two sites. (a) Option I is based on the correlation the susceptibility maxima and minima: sf1-lb1, sf2-lb2, sf4?-lb3, sf5-lb4, sf6-lb5, sf7-lb6 and sf8-lb8. (b) Option II results from correlating sf1-lb1, sf2-lb2, sf3-lb3, sf5-lb5, sf6-lb6, sf7-lb7 and sf8-lb8.

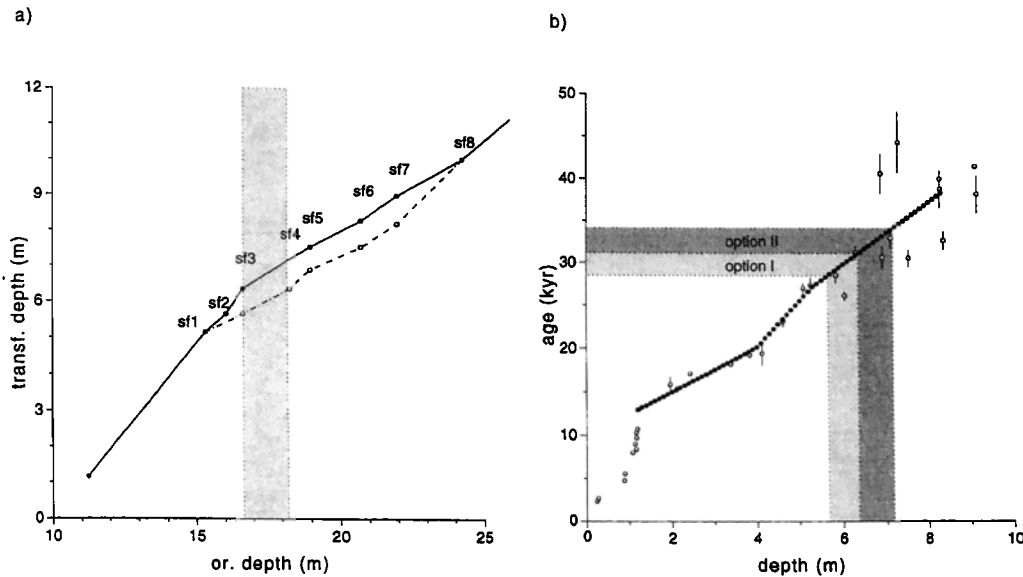
ka (Figure 12). For these intervals, the Lac du Bouchet depth-time transformation is based on radiocarbon dating [Thouveny *et al.*, 1990]. Hence, the above mentioned ages are  $^{14}\text{C}$  ages.

The thickness of the excursions interval in Lac St. Front is 1.6 m original depth. In both correlation options the thickness of this interval is transformed to  $\sim 0.8$  m. This corresponds to a time period of  $\sim 3$  kyr. The part of the excursion with shallow and negative inclinations has a thickness of 0.4 m in Lac St. Front, corresponding to an apparent duration of  $\sim 0.8$  kyr.

Although the depth transformations suggest that both correlation options are acceptable (Figures 11 and 12a), two arguments favor correlation option II. First, in correlation option I the lower susceptibilities at 9 m depth in the Lac du Bouchet sequence (lb7) do not correlate with a susceptibility minimum of the Lac St. Front sequence, while in option II, all well-defined susceptibility minima of Lac du Bouchet correlate with susceptibility minima of Lac St. Front. Second, in correlation option I the sus-

ceptibility minimum lb4 of the Lac du Bouchet sequence is correlated with the susceptibility minimum sf4?. The dubious correlation point sf4? is not used in option II.

Depth transformation of the Lac St. Front paleomagnetic record according to correlation option I shows that this option provides a satisfying correlation of the Lac St. Front and Lac du Bouchet paleomagnetic records only for the upper 4.9 m; below this depth the correlation between these records is poor (Figure 13). Option II, however, correlates the directional records of Lac St. Front and Lac du Bouchet over the entire section (Figure 14), for example, the shallow inclinations accompanied with westerly declinations at 1.8, 2.9, and 4.9 m (transformed) depth and the directional variations between 4.8 and 6 m (transformed) depth. The slight differences between the depths of these characteristic directional variations at the two sites can be explained by a moderately accurate susceptibility correlation (1-4.9 m transformed depths) and by small differences in NRM acquisition.



**Figure 12.** (a) Comparison of LSF original depths with the transformed depths, after correlation options I (open circles, dot-dashed line) and II (solid circle, solid line). The shaded area marks the excursions interval of Lac du Bouchet. (b) Depth-time transformation of Lac du Bouchet. Open circles with error bars denote the individual <sup>14</sup>C dating points; solid circles denote the regression lines calculated after rejection of unreliable <sup>14</sup>C data points [Thouveny et al., 1990]. The light (dark) gray area marks the position of the excursions interval according to correlation option I (II).

Concerning the interval with the excursions directions in Lac St. Front, the corresponding Lac du Bouchet interval shows a similar succession in declinations and inclinations. However, the amplitude of these directional variations in Lac du Bouchet is smaller and does not fall outside the range of paleosecular variation.

To compare normalized NRM intensities of Lac St. Front with those observed in Lac du Bouchet, NRM/IRM ratios of Lac du Bouchet [Thouveny et al., 1993] were also classified into two groups (I and II). As rock magnetic properties of the Lac du Bouchet sediments differ from those of the Lac St. Front sediments, different rock magnetic criteria were chosen for this classification. NRM/IRM ratios, whose associated rock magnetic parameters satisfy the following criteria:  $500 \cdot 10^{-8} \text{ m}^3/\text{kg} < \chi < 700 \cdot 10^{-8} \text{ m}^3/\text{kg}$ ,  $40 < \text{IRM}/\text{ARM} < 55$ ,  $100 \text{ kA/m} < \text{IRM}/\chi < 150 \text{ kA/m}$ ,  $2 \text{ kA/m} < \text{ARM}/\chi < 3.5 \text{ kA/m}$  are classified into group I and are considered as reliable recorders of the intensity changes of the geomagnetic field. NRM/IRM ratios associated with rock magnetic parameters which do not satisfy one of the mentioned criteria are classified into group II.

For the Lac du Bouchet sediments, 382 NRM/IRM ratios were classified into group I and 386 were classified into group II. At 6.8 m depth the lowest NRM/IRM ratios are observed. Because of the presence of some lower susceptibilities in this interval, this minimum is partially carried by NRM/IRM ratios belonging to the 'unreliable' group II (Figures 13 and 14). However, the lowest NRM/IRM ratios belonging to group I are also found at this depth. Following option I, this NRM/IRM minimum has no clear equivalent in the Lac St. Front record (Figure 12), while according to option II, this minimum correlates with the major NRM<sub>15</sub>/IRM minimum accompanied by the excursions directions (Figure 14). Hence the normalized NRM intensity records provide an additional support for option II.

To summarize, correlation of the Lac St. Front and Lac du Bouchet susceptibility records reveals two correlation options.

Option II is more satisfying, because (1) it provides a slightly better susceptibility correlation and (2) it also correlates, in contrast to option I, the paleomagnetic records

### Absence of These Excursions Directions in Lac du Bouchet

Because of the small geographical distance between Lac St. Front and Lac du Bouchet, the absence of this excursion in Lac du Bouchet cannot be explained by a different geomagnetic signal. The most probable remaining explanation for the absence of this excursion in Lac du Bouchet is that the geomagnetic signal is more smoothed in this sedimentary record. In this section the validity of this explanation will be checked.

The Lac du Bouchet interval, corresponding to the excursions directions of Lac St. Front, has a similar inclination pattern. Declinations in both records are characterized by dominantly westerly declinations. The main difference between the two records is that the amplitude of the directional variations is much smaller in Lac du Bouchet than in Lac St. Front. The fact that similar directional variations patterns are found in a smoothed form in Lac du Bouchet, together with a lower sedimentation rate (~25 cm/kyr) than that in Lac St. Front (~40 cm/kyr), favors the explanation that the absence of excursions directions in Lac du Bouchet results from smoothing of the geomagnetic signal.

Thouveny and Creer [1992] showed that smoothing of the geomagnetic signal may explain the absence of the Laschamp excursion in the Lac du Bouchet record. Smoothing may explain the absence of excursions in sedimentary records, if the acquisition of the NRM takes longer than the duration of a geomagnetic excursion. In this case, excursions directions are overprinted by normal field directions and are thus not, or only partially, visible in the paleomagnetic records. The effect of smoothing of excursions

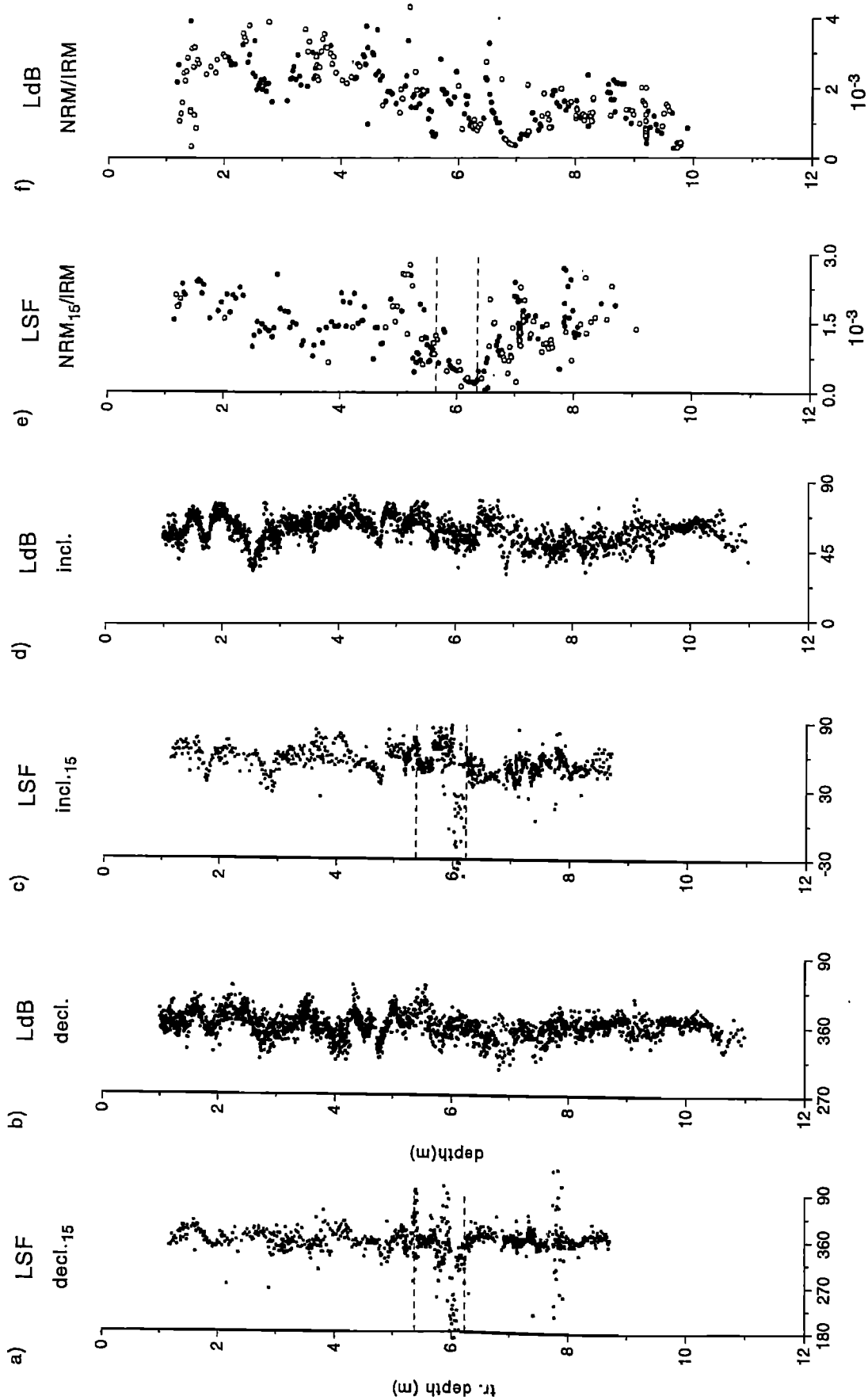


Figure 13. (a, c, e) Lac St. Front paleomagnetic records plotted on the transformed depth scale after correlation option I. and (b,d,f) comparison of these record with the Lac du Bouchet paleomagnetic records. Outliers are removed in the (Figure 13 b) declination and (Figure 13d) inclination records of Lac du Bouchet [Thouveny et al., 1990]. Records for the relative NRM intensities (Figure 13 e; NRM<sub>15</sub>/IRM, Lac St. Front, Figure 13f; NRM/IRM, Lac du Bouchet) show two types of data points, solid (open) symbols denote NRM/IRM ratios classified into group I (II) (see text). Dashed and dot-dashed lines denote the upper and lower limit of the excursions directional interval in Lac Front. Note that below 4.9 m depth the paleomagnetic records do not correlate anymore.

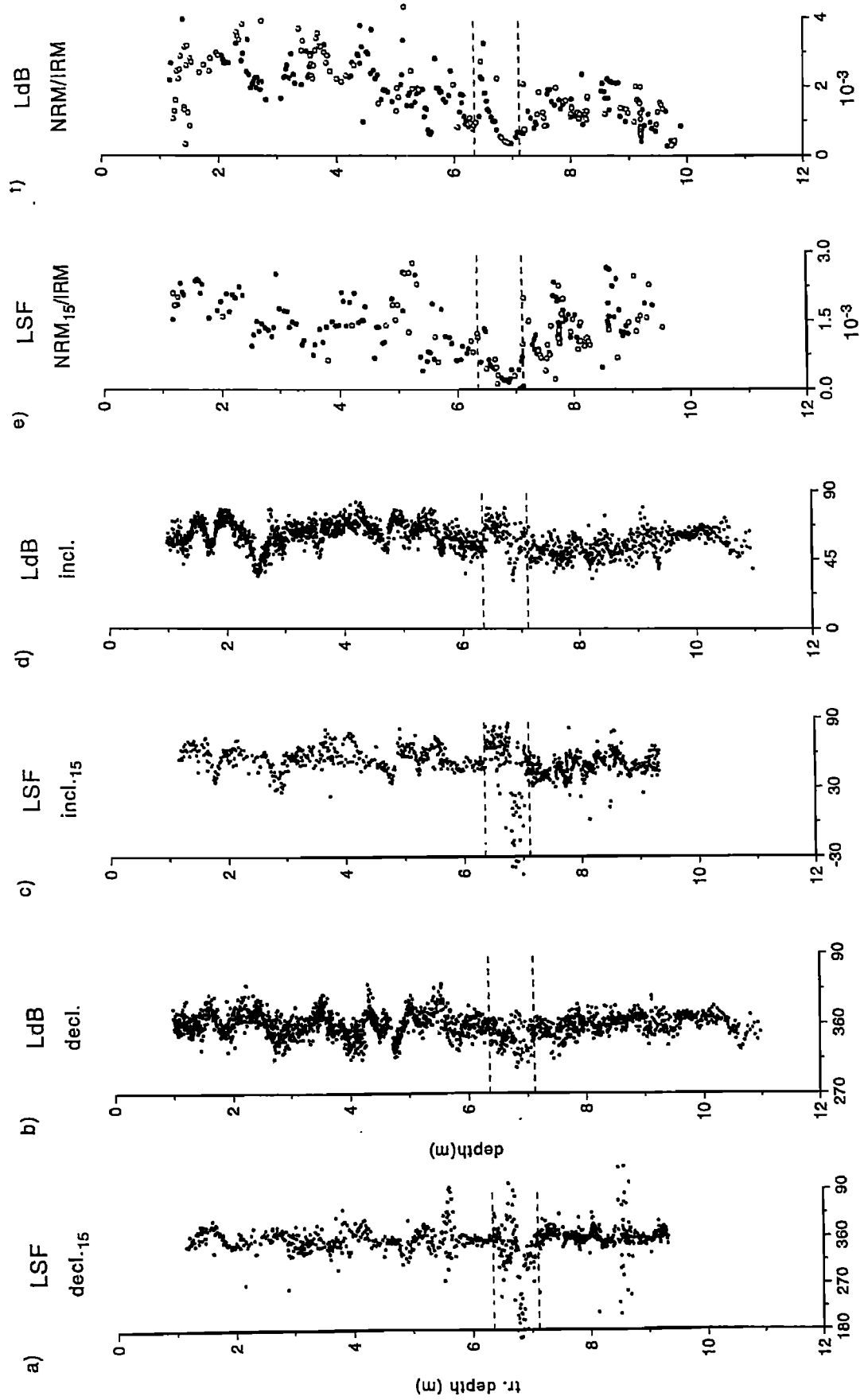


Figure 14. Comparison of the (a, c, e) Lac St. Front paleomagnetic records plotted on the transformed depth scale after option II with the (b, d, f) Lac du Bouchet records. Same symbols and lines as in Figure 11. Note that these records correlate throughout the entire section.



sional directions might be large, if we take into account that excursions occur in a lower-intensity field than the "normal" directions just after the excursions do [Coe and Liddicoat, 1994; Quidelleur and Valet, 1994].

Sedimentation rates are a factor 1.5 to 1.7 higher in Lac St. Front than in Lac du Bouchet (Figure 12). Assuming that the NRM in both records is carried by a postdepositional remanent magnetization (pDRM) and that the lock-in depth for the pDRM signal is the same at both sites, the temporal resolution of the Lac St. Front paleomagnetic records is higher than that of the Lac du Bouchet records. In this case, a smoothed directional record of Lac St. Front should provide results similar to those provided by the unsmoothed directional records of Lac du Bouchet.

A simple model to smooth the paleomagnetic signal of Lac St. Front will be presented here. In a first step, declination, inclination and NRM<sub>15</sub> intensity records of Lac St. Front were transformed to the Lac du Bouchet depth scale, in order to compensate for the relative changes in sedimentation rates between the two sites. In a second step, magnetization vectors were calculated for each stratigraphic depth. Then the smoothing was applied by computing average magnetization vectors using a triangular window of 20 cm width [Rochette, 1990]. This window was slid in 3 cm steps along the whole section. It should be noted that such a triangular window corresponds to a half fixing depth of 10 cm, as suggested by Hyodo [1984].

After application of this procedure the amplitude of the smoothed inclination feature across the excursion is the same as the amplitude of the measured inclination variations observed in the corresponding Lac du Bouchet interval (Figure 15). Concerning the declinations, amplitude variations of the smoothed signal remain somewhat larger than the declination variations in the corresponding Lac du Bouchet interval (Figure 15).

Inclination and declination changes in the upper part of the smoothed Lac St. Front record are still visible after application of this triangular window. Furthermore, these smoothed inclination and declination variations can be correlated with the non smoothed declination and inclination variations in the upper part of the Lac du Bouchet record (Figure 15). Comparing the original directional records of Lac St. Front with their smoothed records also shows that the directional variations in the upper part of Lac St. Front are less smoothed than the excursions (Figures 14 and 15). This finding can be explained by the fact that the directional oscillations in the uppermost part of Lac St. Front have occurred in relatively long periods and are not accompanied by lower NRM<sub>15</sub> intensities, whereas the excursion is characterized by large directional fluctuations in short periods, accompanied with low intensities. The larger effect of smoothing on low NRM<sub>15</sub> intensities can be easily demonstrated, in the case in which the triangular window partially covers the excursions directions accompanied by low NRM<sub>15</sub> intensities and partially covers the "normal" NRM<sub>15</sub> directions accompanied by higher intensities. It is obvious that in this case the averaged directions are relatively more influenced by the directions with the higher NRM<sub>15</sub> intensities. This finding explains why the shallow and negative inclinations of Lac St. Front, occurring only in a 20-cm-thick transformed depth interval, are so easily smoothed by a triangular window of 20 cm width.

A disadvantage of this smoothing model is that not only directional variations acquired in a low intensity field are easier averaged out, but also the directional variations in low magnetic

concentration intervals. To avoid this undesirable effect, one might consider calculating the magnetization vectors with the help of normalized NRM<sub>15</sub> intensities. On the other hand, we argued that about one third of the total number of NRM<sub>15</sub>/IRM ratios might be unreliable recorders of the paleointensity field. This argument implies that another error might be introduced by applying of our smoothing model to magnetization vectors calculated with the help of normalized NRM<sub>15</sub> intensities.

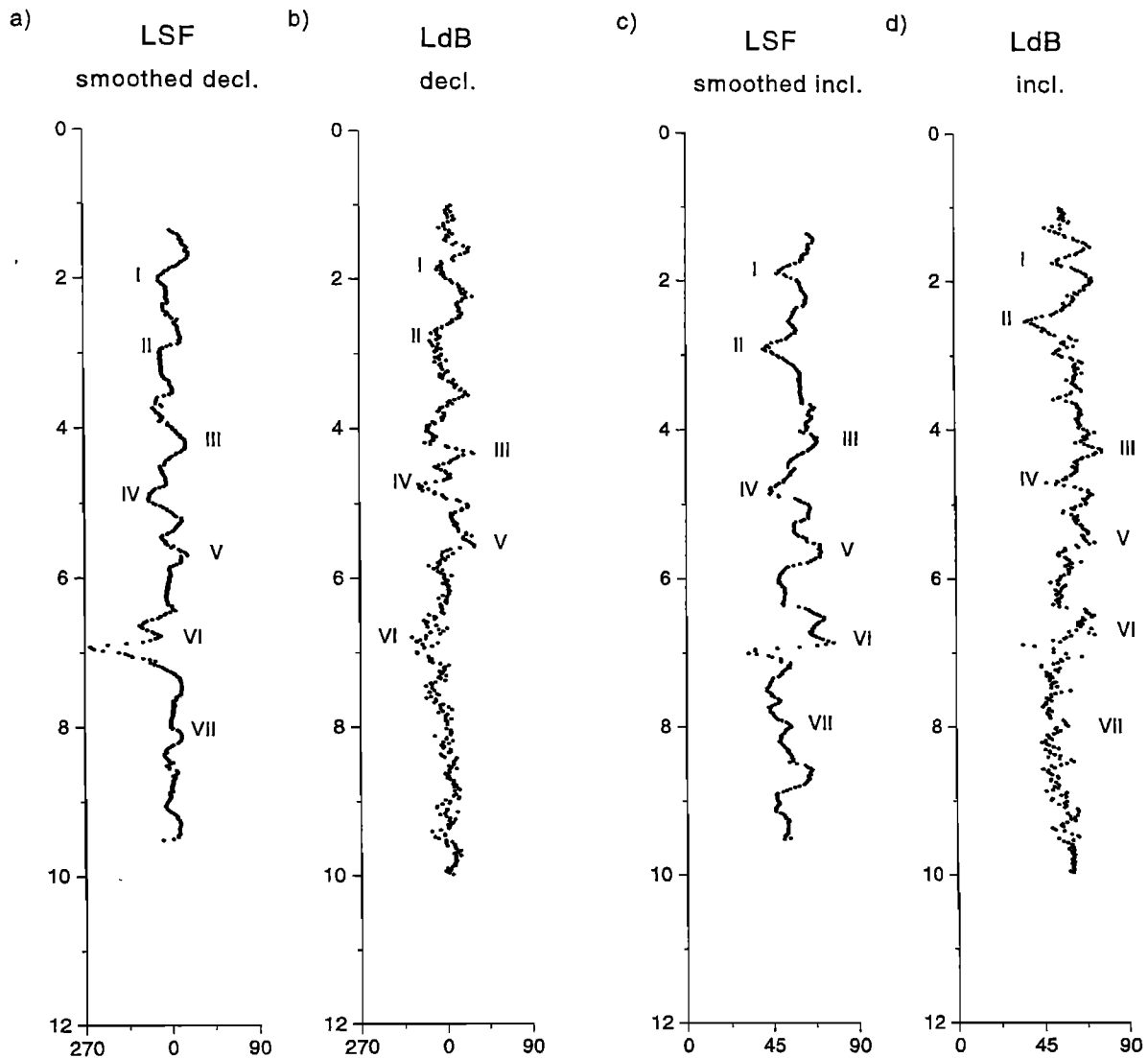
Application of this triangular window shows mathematically that the smoothed directional records of Lac St. Front are similar to the unsmoothed directional records of Lac du Bouchet. The most striking smoothed directional features of Lac St. Front correlate with the striking directional variations recorded in Lac du Bouchet (Figure 13). This resemblance suggests that both records reflect secular variation patterns and that the excursions recorded in Lac St. Front reflect an excursion of the geomagnetic field, because, if the directional variations observed in Lac St. Front result from sedimentary artefacts, tilt/deformation, or misalignment of the magnetic grains, it is unlikely that a smoothed form of these variations would be found in Lac du Bouchet. However, we emphasize that the correspondence between the two records does not imply that the excursions in Lac St. Front reflect exact directional changes in the geomagnetic field. It is more reasonable to assume that the excursions in Lac St. Front is also affected by pDRM smoothing.

Calculating the virtual geomagnetic poles (VGPs) of the excursions in Lac St. Front shows that VGPs with a latitude of <60° are dominantly confined to longitude bands between 270° and 330° (over the Americas). However, because of the effects of smoothing processes on the NRM signal [Rochette, 1990; Langereis et al., 1992; Quidelleur et al., 1994], the significance of confined VGP paths in terms of geomagnetic variations is a matter of debate.

## Mono Lake or Laschamp Excursion

The most probable correlation between the Lac St. Front and the Lac du Bouchet sedimentary sequence suggests an age of ~33 <sup>14</sup>C ka for the excursions directions. However, because of the difference between <sup>14</sup>C ages and calendar ages, evidenced by twin series of datings on coral reef sequences [Bard et al., 1990], the calendar age of the excursion is probably ~4 kyr older (37 ka B.P.)

Two well documented excursions are reported in this period: the Mono Lake excursion and the Laschamp excursion. The first one was discovered at Mono Lake, California by Denham and Cox [1971]. Its existence was confirmed by Liddicoat and Coe [1979], Palmer et al. [1979], Negrini et al. [1984] and Liddicoat [1992]. The age of the Mono Lake excursion is nowadays reported at ~28 ka <sup>14</sup>C age [Liddicoat, 1992; Coe and Liddicoat, 1994]. All detailed records of the Mono Lake excursion are reported from sites in the southwest United States. Excursion directions, which might correspond with the Mono Lake excursion were reported from sites in Norway [Lovlie and Sandnes, 1987], in Baffin Bay [Thouveny, 1988] and in the Arctic Ocean [Lovlie et al., 1986; Bleil and Gard, 1989; Nowaczyk et al., 1994]. The detailed records of the Mono Lake excursion recorded at Wilson Creek, Mill Creek and Warm Springs [Liddicoat, 1992; Coe and Liddicoat, 1994] show an older part containing a westerly declination swing and shallow inclinations



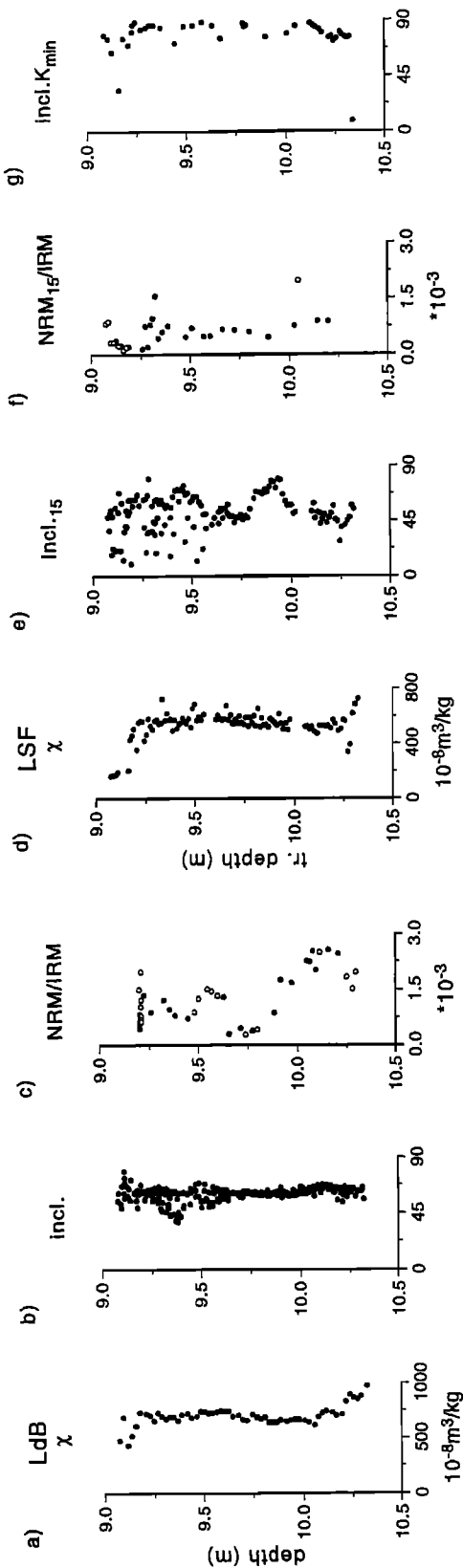
**Figure 15.** Smoothed (a) declination and (c) inclination record of Lac St. Front after application of a triangular window of 20 cm width (transformed depth after option II), compared with the (b) declination and (d) inclination records of Lac du Bouchet calculated after application of a moving box window of 2 cm width. The Lac du Bouchet directional records were filtered to obtain a better comparison with the smoothed Lac St. Front record. Labels indicate the correlation points between these records. Correlation point VII is only observed in the inclination records.

and a younger part, containing easterly declinations and steep inclinations. Especially, the similarities between the inclinations of the Mono Lake records and those of this excursion are striking. We emphasize, however, that this argument cannot, of course, be used to attribute this excursion to the Mono Lake excursion. This because, (1) all excursions might be caused by similar changes of the geomagnetic field, and (2) because of NRM acquisition processes all probably sedimentary records of excursions do not reflect exact changes of the geomagnetic field during these periods.

The Laschamp excursion was first discovered by *Bonhommet and Babkine* [1967] on the Laschamp lava flows (Chaîne des Puys, Massif Central, France). The presence of anomalous directions during this period was confirmed by paleomagnetic studies of other lava flows in the French Massif Central by *Chauvin et al.* [1989]. Paleointensity determinations revealed that the anomalous directions of the Laschamp excursion are ac-

companied by extremely weak field intensities [*Roperch et al.*, 1988; *Chauvin et al.*, 1989]. A compilation of all reported ages of the excursive lavas in the Chaîne des Puys was made by *Thouveny and Creer* [1992]. Taking into account only the K/Ar and Ar/Ar ages, these authors found a weighted age of  $44.56 \pm 13.66$  kyr for the Laschamp excursion. Using all available ages, including thermoluminescence ages, they found an average age of  $35.13 \pm 15.66$  ka B.P for this excursion. Concerning the error bars, these authors took as standard deviation 2 times the inflection point of a Gaussian distribution ( $2\sigma$ ). During the same time period, abnormal paleomagnetic directions were found on the Icelandic lavas of the Skalamaelifell [*Kristiansson and Gudmundsson*, 1980; *Levi et al.*, 1990].

According to option I, the age of our excursion is the same as the age of the Mono Lake excursion. However, according to the most satisfying and probable correct correlation option (II), the estimated age of the excursion recorded in Lac St. Front (37 kyr)



**Figure 16.** Down-core records of (a) susceptibility, (b) inclination and (c) NRM/IRM of Lac du Bouchet for the 9.1–10.3 m depth interval. Records of (f) susceptibility after 15 mT AF demagnetization, (h) NRM<sub>15</sub>/IRM and  $K_{\min}$  inclination for the corresponding interval in Lac St. Front. Note that depths in Lac St. Front are plotted on the Lac du Bouchet depth scale. Original Lac St. Front depths for this interval are between 21.9 and 24.7 m. In the normalized NRM<sub>15</sub> intensity records (open) closed symbols denote NRM<sub>15</sub>/IRM ratios belonging to group I (II) (see text).

falls between the reported ages of the Mono Lake and the Laschamp excursion. Because of (1) uncertainties in the estimated age of the excursions interval in Lac St. Front (Figure 9b), (2) uncertainties in the exact difference between <sup>14</sup>C ages and calendar ages, and (3) the variations in the reported ages of the Laschamp excursion, chronological arguments can hardly be used to decide whether the excursion recorded in Lac St. Front corresponds with the Mono Lake or Laschamp excursion.

We tend to attribute this excursion to the Laschamp excursion for the following reason: The minimum NRM<sub>15</sub>/IRM ratios associated with the excursions directions are the lowest relative NRM<sub>15</sub> intensities in this part of the Lac St. Front sequence. The lowest reliable NRM/IRM ratios in the Lac du Bouchet record are observed in the corresponding interval. Hence these records suggest that the major paleointensity minimum during the time interval 12–45 kyr takes place at ~33 kyr <sup>14</sup>C age. In relative paleointensity studies of the marine sediments, a major paleointensity minimum is often reported at ~40 kyr B.P. [Tauxe and Wu, 1990; Tric et al., 1992; Meynadier et al., 1992; Yamazaki and Ioka, 1994; Weeks et al., 1995]. Although in these records this paleointensity minimum is not accompanied by excursions directions (probably a stronger effect of smoothing of the directional signal due to the lower sedimentation rates), it is likely that the paleointensity minimum in the marine records at ~40 kyr ago correlates with the one of the Lac St. Front and Lac du Bouchet records, dated ~33 kyr <sup>14</sup>C. This correlation implies that the excursion recorded is the expression of the Laschamp excursion. In this case a possible explanation for the absence of the Mono Lake excursion is that because of its (very) short duration this excursion is not fully expressed in the paleomagnetic records of Lac St. Front. A smoothed expression of the Mono Lake excursion might be seen at 16 m depth (5.8 m transformed depth, option II) in the Lac St. Front sequence. This small interval is characterized by an easterly declination swing (up to 90° east) and steep inclinations (75°–80°) and has, according to the Lac du Bouchet depth-time transformation, an age of 28 kyr <sup>14</sup>C. Another possible explanation for the absence of the Mono Lake excursion is that this excursion is a local feature of the geomagnetic field, which did not occur in Western Europe.

In the less probable case that the excursion in Lac St. Front corresponds to the Mono Lake excursion, the most likely explanation for the absence of the Laschamp excursion is that the Laschamp excursion occurred during a temperate period of the midglacial and that because of a higher total organic matter content, lower sedimentation rate, and slightly different magnetic properties the Laschamp excursion is smoothed. Another possibility is that the Laschamp excursion is recorded deeper in the Lac St. Front sequence. At 9.8 m depth (~43 kyr <sup>14</sup>C) in the Lac du Bouchet sequence, another minimum in normalized NRM intensities is observed (Figure 16). In contrast to the normalized NRM intensity minimum at ~33 kyr <sup>14</sup>C, no particular declination and inclination swing is observed at 9.8 m depth [Thouveny et al., 1990]. The latter observation disfavors the occurrence of an excursion at this interval. Nevertheless, it is likely that in the hypothetical case that the Laschamp excursion is recorded deeper in the Lac St. Front sequence, it is observed in the interval that corresponds to 9.8 m depth in Lac du Bouchet. Unfortunately, only two parallel cores cover this interval in Lac St. Front. One of these cores (core B) was cored not with a piston but with a rotating Mazier corer. Moreover, the slightly lower  $K_{\min}$  inclinations (Figure 16g) suggest a disturbed magnetic fabric in this interval. (These are the main reasons to cut off the above present-

ted Lac St. Front paleo-magnetic records at 22.4 m depth). From this data set it can be shown that inclinations are scattered and  $\text{NRM}_{15}/\text{IRM}$  ratios are constant but systematically lower than those in the higher part of the Lac St. Front sequence (Figure 16). It is uncertain whether these lower  $\text{NRM}_{15}/\text{IRM}$  ratios result from a low paleointensity field or from a poor alignment of the magnetic grains due to the disturbed magnetic fabric. A correlation with Lac du Bouchet is absent for this interval, and no indication for the presence of a geomagnetic excursion around  $\sim 43$   $^{14}\text{C}$  kyr exists.

Because of the discrepancies between  $^{14}\text{C}$  ages and calendar ages and the large error bars in the weighted age of the Laschamp excursion, the difference between the reported ages of the Mono Lake and the Laschamp excursion is too small to assume a priori that these two reported excursions have a different geomagnetic origin. For example, in the likely case that 28  $^{14}\text{C}$  kyr corresponds to 31-32 kyr B.P., the Mono Lake excursion cannot be statistically distinguished from the Laschamp excursion;  $44.56 \pm 13.66$  K/Ar-Ar/Ar age [Thouveny and Creer, 1992]. The absence of reliable sedimentary records showing the existence both the Mono Lake and the Laschamp excursion may support this uncertainty. Therefore additional high-resolution paleomagnetic studies and dating are required to check whether the Mono Lake and Laschamp excursion can be distinguished on chronological and paleomagnetic grounds.

## Conclusions

Detailed rock and paleomagnetic records of the Lac St. Front Maar lake sediments reveal the presence of anomalous NRM directions between 16.6 and 18.2 m depth. These directions are accompanied by low NRM intensities and a slightly different NRM behavior. Rock magnetic and AMS data tend to support a geomagnetic origin of this directional and intensity anomaly. Therefore we conclude that these anomalous directions reflect a geomagnetic excursion, which occurred in a low-intensity field.

Smoothing of the magnetization directions of this excursion, by using a 20 cm triangular window, provides a directional signal similar to the NRM directions recorded in the corresponding Lac du Bouchet interval. Hence the absence of this excursion in the Lac du Bouchet record may be explained by smoothing of the geomagnetic signal.

The estimated radiocarbon age of this excursion is 33 kyr B.P.. This age can be corrected to 37 kyr B.P., as suggested by the differences between  $^{14}\text{C}$  ages and calendar ages [Bard et al., 1990]. Considering the dating errors around the ages reported for the Mono Lake ( $\sim 28$   $^{14}\text{C}$  kyr) and the Laschamp excursion ( $44.56 \pm 13.66$  K/Ar-Ar/Ar age), it is difficult to decide which is the one described here. Moreover, it cannot be completely excluded on statistical grounds that these two reported excursions represent one geomagnetic event. Considering that the paleointensity minimum associated with this excursion is often recorded at  $\sim 40$  ka B.P. in marine records and assuming that the Mono Lake and Laschamp represent two excursions, we tend to attribute this excursion to the Laschamp excursion.

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